ORIGINAL ARTICLES

Potable Water and Terrestrial Resources on Grand Bahama Post-Hurricane Dorian: Opportunities for Climate Resilience

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DOI: https://doi.org/10.15362/ijbs.v28i0.467

Abstract

The catastrophic impact of Hurricane Dorian in September 2019 was unprecedented for the island of Grand Bahama. Flooding in the western portion of the island damaged pine ecosystems, inundated the soil and groundwater with salt water, and disrupted potable water service throughout the island. More than two years post-Hurricane Dorian, the freshwater lenses that the island relies on for potable water are still inundated with salt water. This collaborative paper summarizes all efforts of researchers and practitioners to evaluate the freshwater lenses, as well as their associated ecosystems, that serve as the main source of drinking water for the island of Grand Bahama. Hydrogeologic and vegetation assessments were conducted on the two primary wellfields that provide 95% of the drinking water to the island, over the span of two and a half years from the immediate aftermath of Hurricane Dorian through present day. While salinity and total dissolved solid concentrations in groundwater have declined, present levels indicate that the full recovery of the freshwater lenses may take decades. Forest assessments indicate that in Wellfield 6, which was

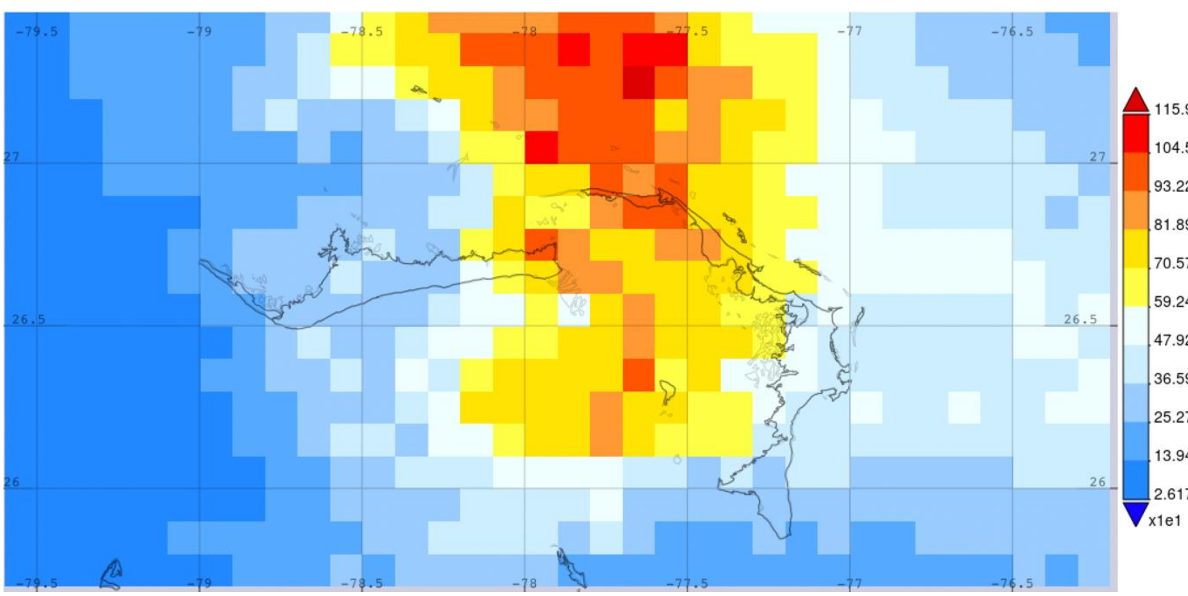
the primary source of potable water pre-Hurricane Dorian, the pine forests suffered significant damage with complete pine mortality and little regeneration of pine trees occurring, which could impact the underlying freshwater lens. Lessons learned from this event underscore the vulnerability of water resources in The Bahamas and the critical need for adaptation strategies to improve resilience to future extreme events and climate change.

Introduction

Between September 1-3, 2019, Hurricane Dorian devastated the islands of Abaco and Grand Bahama. Classified as Category 5 hurricane on the Saffir-Simpson Hurricane Wind Scale, Hurricane Dorian became the strongest hurricane to impact The Bahamas in recorded history, with wind speeds over 296 km/h (184 mph; Avila et al., 2020; Cerrai et al., 2020). On September 2, the hurricane made landfall over the eastern end of Grand Bahama and stalled over the island for more than a day (Caribbean Disaster Emergency Management Agency, 2019; Cerrai et al., 2020). Estimated accumulated precipitation of greater than 1000 mm occurred over the course of three days in eastern portions of the island (Cerrai et al., 2020; see Figure 1). Storm surge and flooding led to a measured water level over 2 m greater than the mean water high tide in western portions of Grand Bahama and upwards of 6.4 m of flooding in some regions (Avila et al., 2020). On September 4, after the passing of the hurricane, approximately 14% of the island was still flooded (Cerrai et al., 2020).

Figure 1

Map of Total Accumulated Precipitation for the Period September 1-4, 2019, Derived from NASA IMERG v06 Final Run.



Note: The graph was generated using the NASA GIOVANNI system (https://giovanni.gsfc.nasa.gov/).

Grand Bahama has experienced flooding and saltwater inundation of the freshwater lenses during previous hurricanes. In 1995, storm surge from Hurricane Floyd resulted in significant flooding that inundated the wellfields (U.S. Army Corps of Engineers [USACE], 2004), with observations of inundations up to 1.12 m in some areas (Mazzoni, 2013). Additionally, in 2004 both Hurricanes Jeanne and Frances resulted in approximately 2 m of storm surge and flood waters in the wellfields (USACE, 2004). Following these hurricanes, pumping efforts were undertaken to extract the saltwater inundating the aquifers and to restore the freshwater lens. In portions of Grand Bahama inundation levels after Hurricanes Wilma (2005), Irene (2011), and Sandy (2012) were observed at 2.44 m, 0.6 m, and 1.3 m, respectively (Mazzoni, 2013). While past events caused storm surge and flooding, Hurricane Dorian resulted in the greatest level of flooding at 6.4 m. Imagery analysis indicates that at least 45% of eastern Grand Bahama was flooded due to Hurricane Dorian, with estimates in western Grand Bahama lacking on account of imagery constraints (Cerrai et al., 2020).

Prior to Hurricane Dorian, the island with the second greatest abundance of fresh water in The Bahamas was Grand Bahama (USACE, 2004). The island was solely reliant on groundwater aquifers for its drinking water sources, through freshwater lenses that lie atop denser saline water. Ninety-five percent of drinking water for the island originated from two major wellfields. Prior to Hurricane Dorian, an annual pumping rate of three billion gallons (13 million m^3) of water was obtained from these wellfields, with a recharge rate of 4.5 billion gallons (20.5 million m^3) of water.

As a result of Hurricane Dorian, the two primary wellfields that provided 95% of the water to the island experienced flooding and saltwater inundation. The terrestrial resources of western Grand Bahama were adversely impacted as flooding of the freshwater aquifers persisted for weeks, altering the hydrogeology and ecosystems in the regions of the two primary wellfields. Saline floodwaters physically mixed with underlying fresh water, effectively eliminating the freshwater lens. Consequently, saltwater inundation of the aquifer significantly disrupted potable water provision to the island. In addition, the island experienced widespread mortality of stands of commercial Caribbean Pine (*Pinus caribaea* var. *bahamensis*), saturated soils, and the deposition of a layer of sediment (~6-7 cm thick silt crust) as floodwaters receded. Because vegetation and trees have the potential to influence the thickness of the freshwater lens by drawing water from their roots for transpiration (Comte et al., 2014), pine tree mortality has the potential to impact water availability in Wellfield 1 (W1) and Wellfield 6 (W6).

Drinking water provision on Grand Bahama is managed by the Grand Bahama Utility Company (GBUC), a private utility company. GBUC initially pumped water from the least saline contaminated wells to promote recovery of the freshwater lens (Chaves, 2021). However, due to saltwater inundation of the aquifer and extensive mixing of the freshwater lenses that had occurred during flooding, initial pumping tests proved unsuccessful at remediating the saltwater inundation of the wellfield or restoring the freshwater lenses. This resulted in the distribution of brackish water throughout the residential network, and, therefore, the majority of residents did not have potable water in their homes for approximately one month post-Hurricane Dorian (Turner, 2022). In addition to having to acquire bottled water, residents experienced negative effects in their homes as the high salinity in the supplied water affected infrastructure such as corroded faucets and pipes.

Residents were provided water from alternative sources at no cost from non-governmental organizations and GBUC. Individuals accessed emergency drinking water sources through disaster relief aid organizations, and GBUC collected water from another wellfield on the island, transporting it to specific sites for distribution to residents who lacked potable water in their homes. Given the importance of providing water to eastern Grand Bahama, GBUC was compelled to continue extracting groundwater from the W6, the result of which was the distribution of brackish water for residential consumption. Two years following Hurricane Dorian, 30% of consumers in the distribution network still did not have potable water in their homes. However, complete restoration of potable water service occurred on October 28, 2021, when a portable reverse osmosis system began operation. This system purified saline water that was pumped from the W6 wellfield and distributed to communities.

Due to the unprecedented impact that Hurricane Dorian had on drinking water sources and ecosystems on the island of Grand Bahama, multiple studies have been conducted on the wellfields of the island to assess damage and identify potential solutions. This paper outlines the initial and ongoing assessment and recovery efforts undertaken on the wellfields and their associated ecosystems on Grand Bahama over the two and a half years following Hurricane Dorian. Potential strategies for recovering the wellfields are highlighted, in addition to research opportunities that have emerged from this event.

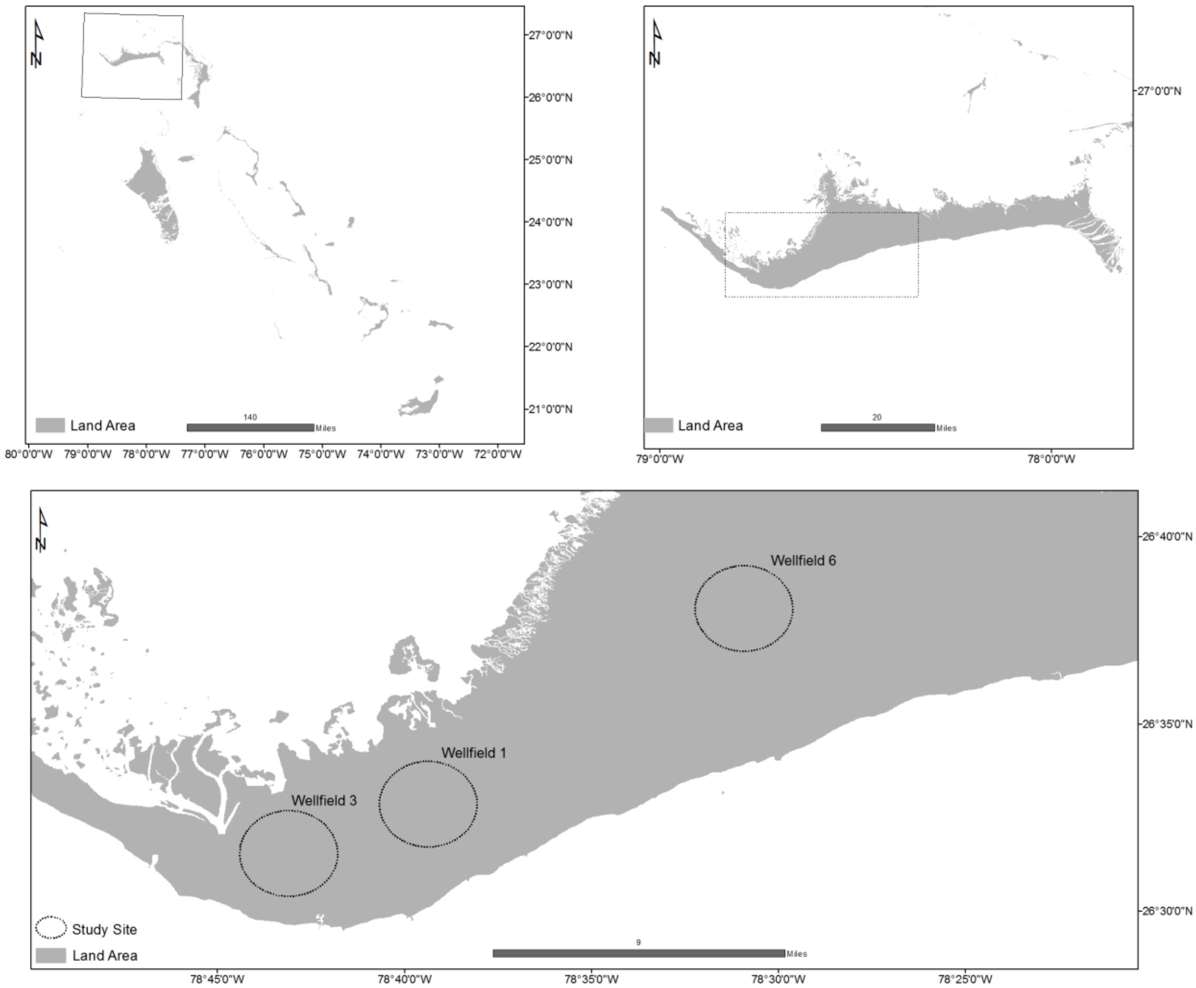
Study Site

Grand Bahama is among the northernmost islands in the Bahamian archipelago and the second most populous island in the country after New Providence. With a land surface of approximately 1,373 km^2, the island is relatively flat with the highest elevation at 20.7 m above sea level (USACE, 2004). Subaerial and subsurface carbonates are the predominant lithology on Grand Bahama, and although not supporting surface waters, they host meteoric groundwater which is controlled by poorly stratified non-skeletal shallow-water limestones of the Pleistocene Lucayan formation (Mylroie et al., 1995; Carew & Mylroie, 1997). This limestone on the Little Bahama Bank is approximately 15–30 m thick and rests on dolomite below; over Grand Bahama, the limestone unit has a nearly uniform thickness of ~20 m (Vahrenkamp et al., 1991). In a study by Whitaker and Smart (2005, p. 862), mean hydraulic conductivity for the Lucayan limestone was determined to be 1200 m/d based on pumping tests at different locations in Grand Bahama.

GBUC manages and extracts groundwater from six wellfields for drinking water supply on the island. The study sites were at two of these locations: Wellfield 1 (W1) and Wellfield 6 (W6), located in the western portion of Grand Bahama (see Figure 2). Prior to Hurricane Dorian, 95% of the drinking water was sourced from these two wells, with 35% of the water extracted from W1 and 60% extracted from W6. Wellfield 3 (W3) provided the remaining 5% of drinking water. W1 is located in an urban area of the northwestern region of the city of Freeport, with land cover primarily consisting of pine forests and residential homes. W6 is located northeast of the city limits and has a land cover of Bahamas pine forests with unpaved dirt roads throughout the region.

Figure 2

Map of Study Site in Western Grand Bahama.



Note: a) The island of Grand Bahama in the archipelago of The Bahamas (location of Inset b marked by the rectangle); b) The island of Grand Bahama (inset c shown in the rectangle); and c) Locations of Wellfield 1 and Wellfield 6 study sites in western Grand Bahama.

Methods: Post-Hurricane Dorian Assessments

Humanitarian Efforts and Assessments led by IsraAID

On September 5, 2019, the day after the passing of Hurricane Dorian, the Israel Forum for International Humanitarian Aid (IsraAID) dispatched an emergency response team to The Bahamas. The team launched a rapid needs assessment to identify areas for intervention. IsraAID and local partners determined to focus on three key sectors: relief item distribution, psychosocial support, and water, sanitation, and hygiene (WASH). IsraAID's efforts pertaining to WASH consisted of two main activities: a two week rapid groundwater assessment and a one year WASH Programme.

IsraAID, in partnership with Israel's Agency for International Development Cooperation

(MASHAV) in the Ministry of Foreign Affairs and the Israel Water Authority, facilitated a local rapid groundwater assessment led by Israel's chief hydrologist. The objective of the rapid water assessment was to conduct field visits to assess water resources post-Hurricane Dorian and to provide recommendations for a long-term water management strategy. Field visits were conducted in the islands of Grand Bahama and Abaco from October 23-29, 2019. The field visits included a groundwater survey of the major wellfields operated by local water utilities on both islands and two blue holes in Grand Bahama (i.e., Owl's and Ben's). The following water quality parameters were measured: electrical conductivity (with profiles taken where possible), pH, and oxidation-reduction potential. A major recommendation from the rapid assessment was the establishment of a WASH programme.

IsraAID's WASH programme ran from September 2020 to August 2021. The WASH programme consisted of two components: a sustainable groundwater management project with four phases and a community outreach initiative. Phase 1 was a groundwater survey, which included geospatial and GPS mapping of water infrastructure (e.g., pumping and observation wells, pumping stations, etc.), in-situ water quality testing, and data collection and analysis for Grand Bahama and Abaco. Water quality parameters (conductivity, pH, temperature, salinity, and total dissolved solids [TDS]) were measured using YSI Quatro Plus meters, and the depth to the water table and bottom of wells were measured using water level meters. All data collected were uploaded to an open-source platform called mWater. The results of the groundwater survey informed the placement of 16 new observation wells (8 on each island) that ranged from 30 ft (9.1 m) to 110 ft (33.5 m) in depth.

For insight into the long-term changes to the freshwater lenses, four observation wells were placed to penetrate the brackish zone (i.e., sentinel wells) while the remaining wells were contained in the freshwater lens and in close proximity to production wells. Each observation well was designed and constructed for extreme weather and equipped with a Solinst Levelogger LTC 5 (a multi-parameter water quality sensor) that would measure temperature, conductivity, and static water level on an hourly basis. Due to the logistical difficulties in manually retrieving well data on Abaco, Solinst LevelSenders were also installed as telemetry devices that would send daily email reports with all measurements via communication networks. The installation of these wells and devices was the objective of Phase 2: to establish a groundwater monitoring network. Phase 3 involved a water management training programme for personnel from both water utilities (i.e., Water and Sewerage Corporation and GBUC) and other local stakeholders as a way of building local capacity. The training included both theoretical and practical aspects, covering 10 topics such as basic hydrogeology, best practices for well data collection and reporting, as well as climate change, resilience, and alternative water supplies and treatment technologies. Phase 4, the final phase, consisted of data interpretation and data management. Databases were developed for both water utilities for the continued monitoring, organizing, and storing of data. The aim of this phase was to help the authorities manage the water resources in a sustainable manner.

Initial Assessments Post-Hurricane Dorian by UNESCO-IHP and Government

On September 8, 2019, in the immediate aftermath of Hurricane Dorian, a team of professionals representing United Nations Educational, Scientific and Cultural

Organization–Intergovernmental Hydrologic Programme, the Water and Sewerage Corporation, and Bahamas Power and Light visited Grand Bahama to assess damage, in collaboration with GBUC. No water resource assessments or measurements were conducted at this time, as the island was still flooded from the hurricane. This visit allowed personnel to conduct visual observations and assess damage in order to mobilize and allocate the required funding.

An expedited groundwater quality assessment was carried out by representatives of the University of Brasilia (Universidade de Brasília) in October 2019, one month post-Hurricane Dorian, to assess the impact of Dorian's storm surge on the quality of the freshwater lens of selected wells of W1 and W6. During this evaluation, salinity, TDS, and electrical conductivity were measured in groundwater from these wells.

Follow up Assessments Post-Hurricane Dorian by University Researchers

Recognizing the need to collect time-sensitive data pertaining to the storm-induced saltwater intrusion on the island of Grand Bahama, a team of scientists from California State University, Sacramento and the Florida Institute of Technology, in collaboration with local engineers and faculty from the University of The Bahamas, conducted a series of field campaigns to assess groundwater and soil salinity on various locations of the island between February and November 2020.

In February 2020, an initial field campaign was conducted, which included the sampling of thirty-eight wells across W1, W3-4, and W6. The parameters sampled included electrical conductivity, TDS, salinity, and temperature. After this initial survey, groundwater samples were collected on a biweekly basis at six wells in W1, three wells in W3 and W4 and nine wells at W6. Sampling was conducted using a REED Instrument SD-4307 SD Series Conductivity / TDS / Salinity Datalogger. Groundwater levels were collected in four wells in W1, seven in W2 and two in W6 using a Solinst 102 Water Level Meter.

Regarding soil sampling, 11 surficial samples were collected four times (May, June, August and November 2020) and one core profile once (May 2020), to determine the distribution of salt within the soil profile and in the surficial soil sediments. Soil samples were taken at depths of 10-15 cm. The soil analysis was conducted by faculty and undergraduate students at the University of The Bahamas Soils Laboratory. The samples were crushed, sieved, and prepared for testing using the saturated paste method.

Follow-up Assessments Two Years Post-Hurricane Dorian by University Researchers and Practitioners

A final field campaign occurred in January 2022 to investigate the recovery of the wellfields more than two years post-Hurricane Dorian. During this site visit a team of researchers from the University of The Bahamas, the Forestry Unit of the Bahamas Ministry of the Environment and Natural Resources, and the University of Brasilia evaluated groundwater, soils, and forests. Soil and water measurements were collected on January 24, 2022 in W1 and January 25, 2022 in W6. Water assessments consisted of sampling four groundwater wells in W1 and seven groundwater wells in W6. Groundwater quality was measured with a Hanna Multiparameter Water Quality meter, model HI98914. Parameters measured included salinity, electrical conductivity, dissolved oxygen, temperature, pH, and TDS.

Soil sampling in January 2022 consisted of sampling four locations at W1 (11 electrical conductivity samples and 13 soil moisture samples) and three locations at W6 (18 electrical conductivity samples and 10 soil moisture samples). At each site, the soil O horizon was cleared away, and a stainless-steel shovel was used to dig a small hole down to bedrock. A plastic auger was used to create a hole to insert soil probes vertically and horizontally; samples for each site were taken in an area with ~ 0.5 m radius. Electrical conductivity (EC) and temperature were analysed using a Hanna HI98331 Groline Direct Soil Conductivity and Temperature Meter, calibrated using HI7031 solution prior to field use (accuracy @ 25 °C: +/- 50 µS/cm, +/- 1°C; resolution: 1 µS/cm, 0.1 °C). Soil moisture (SM) was analyzed using the Extech MO750 Soil Moisture Meter (accuracy: +/- 5% @ 23 +/-5 °C; resolution: 0.1%). Soil colour was described for each site using a Munsell Soil Colour chart under daylight conditions. Hydraulic conductivity was assessed with a single ring infiltrometer (Youngs, 1987).

Forest assessments consisted of evaluating pine tree mortality, tree decay classification, and plant species abundance within sample plots at each wellfield, including four plots in W1 and five plots in W6. Ten-meter diameter circular plots were used. The centre point of each plot was selected 20 m perpendicular to the well site. Each plot was divided into four quadrants using a 5 m radius to each of the cardinal points. In each quadrant, pine trees with crown branches attached and a diameter of 5 cm and greater were measured. For each pine tree, diameter at breast height (1.3 m from the soil surface), tree height, and condition (dead or alive) were recorded. The decay class for dead pine trees was determined using the decay classification system (see Table 1). In each quadrant, the 10 most frequent plant species were also recorded and counted. Data analysis included the determination of available pinewood and the relative abundance of species for each wellfield.

Table 1

Tree Decay Classification System

Decay Class	Description
1	Most branches present: Original branch structure still present with many fine branches still attached
2	Few branches present: Few limbs and no fine branches, sound at base though advancing decay in upper bole
3	No branches/ few stubs only: Predominantly a single trunk, minor stubs, significant decay in all parts of tree

Note: Ministry of the Environment and Natural Resources, Forestry Unit & the International Conservation Corps, 2017.

Evaluation for Managed Aquifer Recharge by University Researchers

In 2021 a study was initiated by a team from the Technical University of Munich (Technische Universität München) to investigate the potential of managed aquifer recharge (MAR) to provide drinking water and to mitigate saltwater intrusion to the freshwater lenses of W6. MAR is the intentional and monitored recharge of water from surface water, rain, or stormwater into an aquifer. The overall goal of MAR is to increase groundwater levels to store water for a time of need or to improve water quality of groundwater which has mixed with infiltrating water (Dillon, 2005). To identify potential suitable locations for MAR on Grand Bahama, a methodology was developed which included hydrological, hydrogeological and geological investigations based on existing data. Several water sources for recharging water under a MAR scheme were investigated.

Results and Discussion

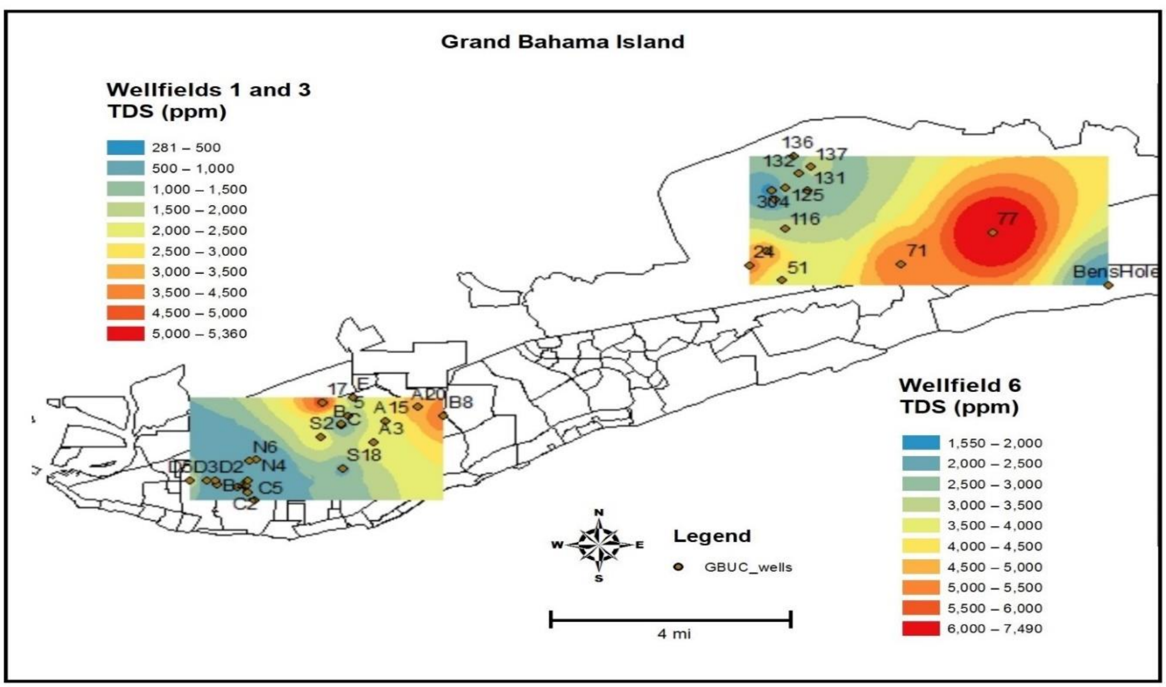
Groundwater

From the 2-week rapid water assessment conducted by IsraAID, the TDS of groundwater in Grand Bahama was approximately 5000 ppm, more than 5-times the maximum recommendations of the World Health Organization (2017). In McClean's Town, Grand Bahama, specific conductivity of groundwater was approximately 2100 µS/cm. From the extensive groundwater survey conducted in Phase 1 in the following year, the impacts to the freshwater lenses on Abaco were determined to be less severe than on Grand Bahama, and recovery to pre-Hurricane Dorian conditions in most of the wellfields was relatively rapid. Data from the observation and sentinel wells cannot be provided as values had an extremely wide range, likely due to data loggers being set too deep in several wells. Loggers were raised to more suitable depths after wells were profiled. This action would allow for more accurate water quality assessments to be carried out in the future.

From the initial post-Hurricane Dorian assessments in October 2019, salinity, TDS, and conductivity levels were elevated in three wells from W1 and three wells from W6. The highest values for all three parameters were observed at W6. An initial map of TDS (in ppm) based on the data collected during the field campaign beginning in February 2020 is shown in Figure 3. As seen from the figure, TDS levels were elevated, well above the drinking water standards with the highest value occurring at W6 (7490 ppm). Out of these 38 wells, 16 were then selected for long-term monitoring.

Figure 3

TDS Concentrations (ppm) Measured in Groundwater in Wellfields 1, 3 and 6 in February 2020.



The data collected during the time period February to November 2020 indicate a very slow recovery process of the freshwater lens system (Figure 4). A year after Hurricane Dorian, elevated levels of salinity were still detected on both the groundwater and soils on most locations on the island, despite the fact that it was a relatively wet year, with significant precipitation levels. The maximum TDS concentrations measured were 845 ppm, 976 ppm and 2510 ppm in W1, W3–4 and W6, respectively (see Figures 4–6).

Figure 4

Comparison of Electrical Conductivity

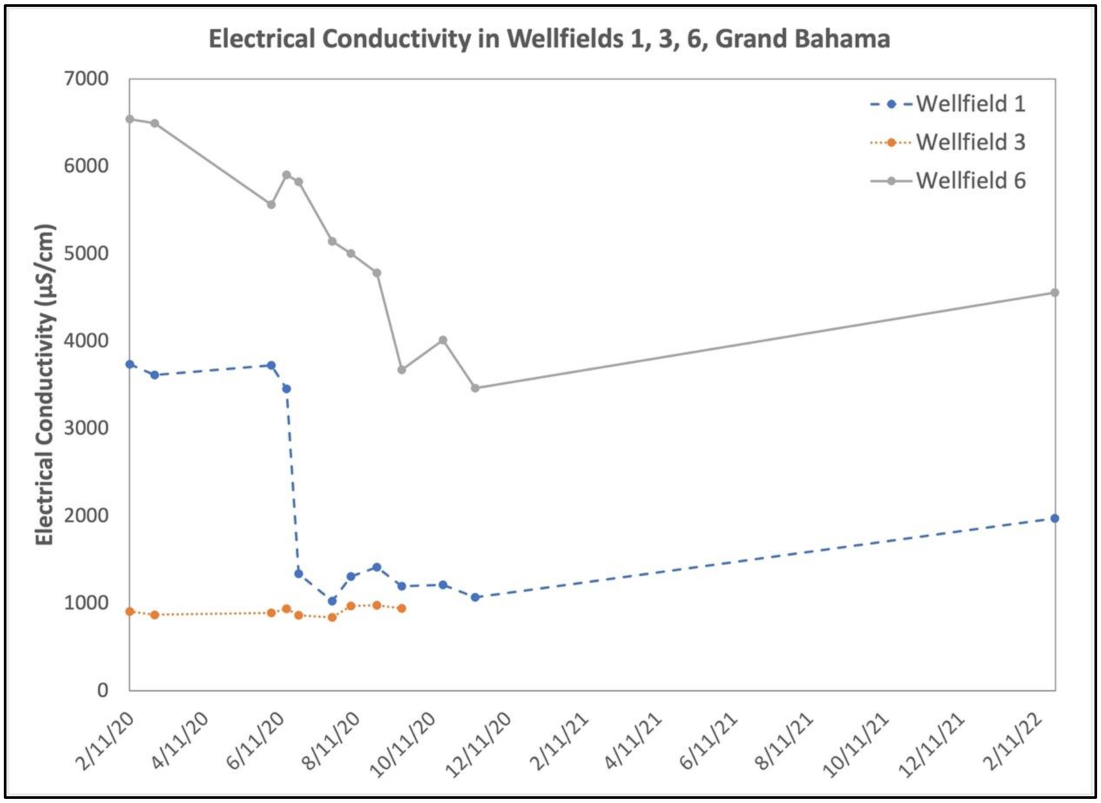


Figure 5

Total Dissolved Solids

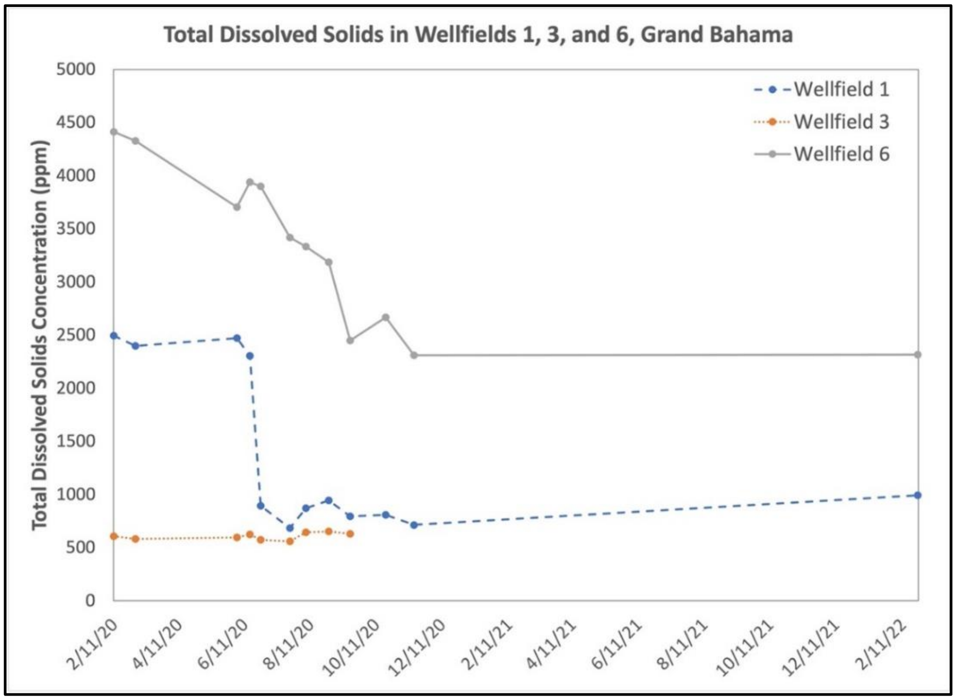
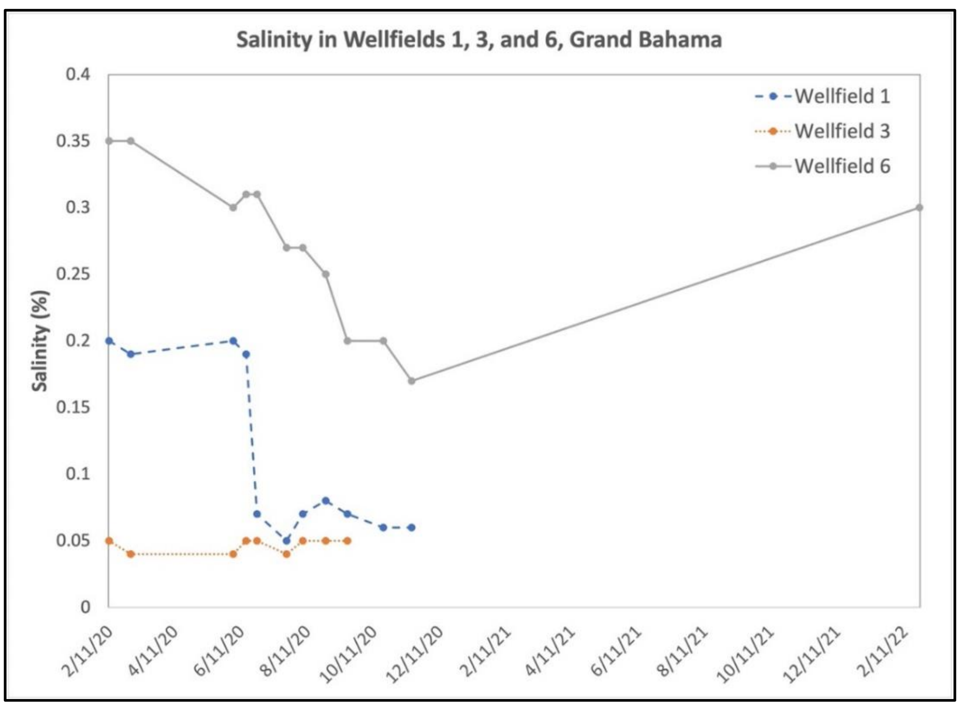


Figure 6

Salinity in Wellfields



In the most recent assessment in January 2022, observations of TDS had declined to an average of 2316 ppm in W6 and 993 ppm in W1. W6 continues to exceed World Health Organization drinking water standards (1000 ppm; 2017). Electrical conductivity levels in W6 were likewise still elevated (2757 – 6326 µS/cm) with W1 exhibiting moderately elevated levels (1657 – 2227 µS/cm). While concentrations have declined for TDS two years following the previous assessment, both electrical conductivity and salinity have increased since the previous sampling campaign. Increasing salinity levels in groundwater could be indicative of the mobilization of salts bound in the soils that are infiltrating the freshwater lens; however, existing salinity levels in the soils indicate that they are not likely a major contributor to salinity. Additional samples need to be collected to investigate this increase in salinity. The high levels that the wellfields exhibit suggest that the wellfield will take many years to recover.

Soils

Soil analyses conducted during the 8-month period from March 2020 to November 2020 revealed that after four rounds of sampling, there was no evidence of salinity clearance for any of the sample points (Table 2). Two years post-Hurricane Dorian, high electrical conductivity (640-3190 µS/cm) and soil moisture (22.6-25.4%) were measured from the silt crust on the forest road shoulder (Table 2, Figure 7), and likely due to poor drainage through the hard limestone track beneath. These values should not be seen as representative of the wider forest area, though, as soil electrical conductivity is moderate in W1 (30-400 µS/cm, Table 2) and in a similar range as W6 (10-250 µS/cm; excluding elevated road shoulder data, Table 2), and when considering probe accuracy (+/- 50 µS/cm), is actually indicative of a reduction in salinity, as compared to two years prior. Thus, the silt crust measured in 2022 is not deemed a major contributor to the salinity of groundwater on Grand Bahama Island. The lower mean electrical conductivity (204 µS/cm, Figure 7) of the silt crust measured in the forest is likely due to leaching through organics observed below. The soil moisture readings from W1 (0.7-16.4%) are comparable to those in W6 (7.6-14.4%, excluding elevated road shoulder data), and when considering 5% probe accuracy. The interrelation of electrical conductivity and soil moisture is indicated by a positive correlation (r^2 0.74), as also found by Zhang et al. (2019).

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Table 2

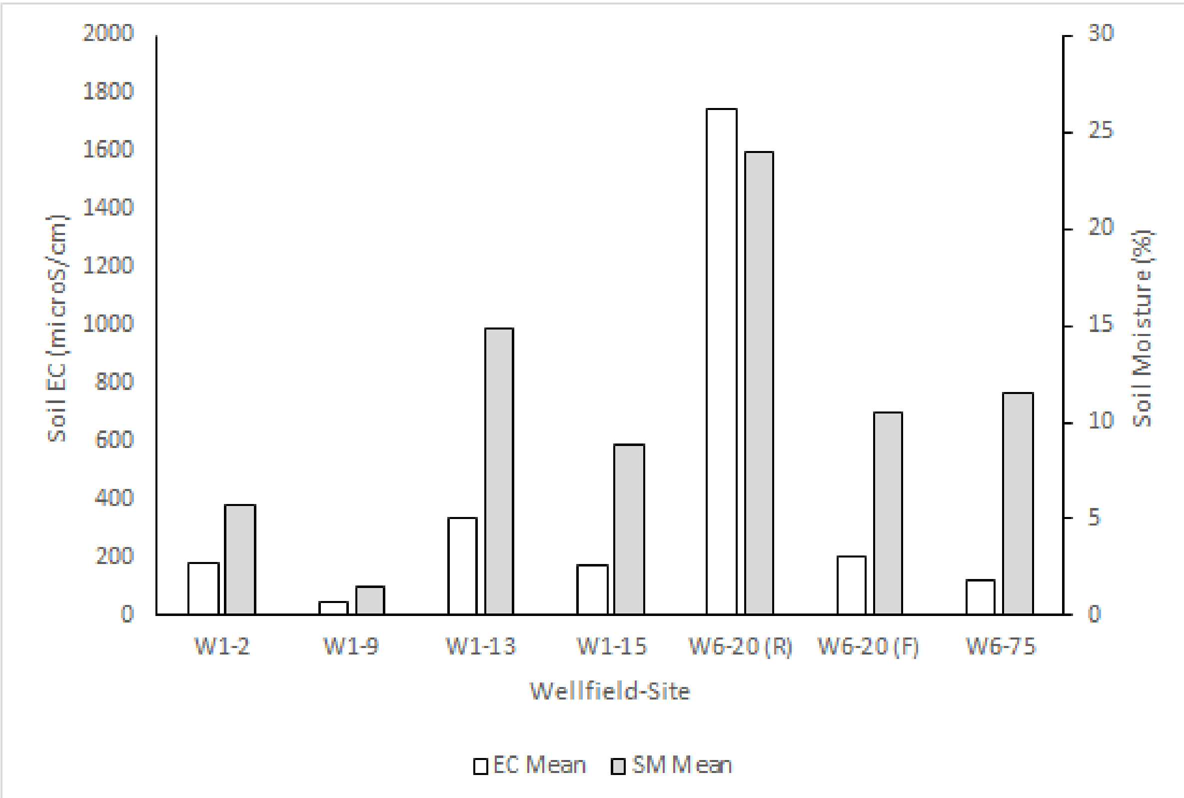
Electrical Conductivity (EC), temperature (T), Salinity, pH, and Total Dissolved Solids (TDS) of soils in Wellfields 1, 3, and 6, Grand Bahama Island

Well field	No. of Samples	Date	EC soil (µS/cm) range	EC soil (µS/cm) mean	T (°C) soil range	Depth (cm) range	Salinity (%)	pH	TDS (ppm)
1	-	7-Mar-20	582-1771	924	-	0-762	-	-	-
	2	29-May-20	1435-1876	1655.5	29.5-29.7	0-10	0.085	7.92	1103
	3	26-Jun-20	1048-1672	1304	29.9-31.1	-	0.067	7.96	868.3
	3	7-Aug-20	878-1085	1002	26.8-27.3	-	0.057	7.96	668
	2	13-Nov-20	498-1112	805	19.4-20.7	-	0.045	7.18	535.5
	1	15-Nov-20	-	0.6	20.7	-	0.030	7.42	388
	11	24-Jan-22	30-400	183.7	20.8-23.8	4-26	-	-	-
3	-	29-May-20	-	-	-	0-10	-	-	-
	2	29-May-20	1066-1594	1.33	29.5- 29.7		0.065	7.89	886
	2	26-Jun-20	1015-1754	1384.5	-		0.070	7.92	922
	2	7-Aug-20	1019-1464	1241.5	27.1-27.3		0.065	7.88	828.5
	3	16-Nov-20	510-767	0.659	19.1-20.7		0.035	7.23	403.5
6	-	29-May-20	-	-	-	0-10	-	-	-
	5	29-May-20	852-1718	1402	29.5 - 29.7	-	0.07	8.09	933.6
	6	26-Jun-20	810-1921	1151.3	19.7-31	-	0.06	7.83	766.5
	7	7-Aug-20	718-1828	1.3	26.9-27.3	-	0.07	7.99	850.1
	18	25-Jan-22	10-3190	775	17.8-23.2	2-12	-	-	-

Note: Sampled from March 7, 2020 through January 25, 2022.

Figure 7

Mean Soil Electrical Conductivity (EC) and Soil Moisture (SM) Measured at W1 and W6, Grand Bahama Island, on 24 and 25 January 2022, respectively



Note: Wellfield 6-Site 20 was differentiated into the silt crust analysed on the road (R) and forest (F).

Forests

Assessments of plant species within the wellfield were conducted to evaluate the ecosystem health of the landscape impacting water quality of the freshwater lens. Thirty-seven different plant species were found during the sampling campaign in January, 26 species in W1 and 31 species in W6, (Table 3). W1 had a higher Shannon diversity index (3) than W6 (1.18), with the top 10 most abundant species in each field accounting for 77% and 81%, respectively. The dominant species (more than 10% relative abundance) made up more than 35% of the species in each wellfield (Table 3). In W1, three species were the most abundant: *Metopium toxiferum* (15%), *Adiantum capillus-veneris* (14%) and *Coccothrinax argentata* (11%). Notably, in W6 only two species, *Coccothrinax argentata* and *Metopium toxiferum* at 18% each, were the most abundant (Table 3). Even though W6 had a greater number of species, the presence of the dominant top 10 species reduced the overall diversity within the sampled plots.

Table 3

Plant Species Abundance and Diversity in Wellfield 1 and Wellfield 6 in January 2022.

Botanical Species	Common Name	W1		W6	
		n =	Relative abundance	n =	Relative abundance
Coccothrinax argentata	Silver thatch palm	202	0.11	605	0.18
Metopium toxiferum	Poisonwood	270	0.15	601	0.18
Byrsonima lucida	Guanaberry	44	0.02	257	0.08
Smilax havanensis	Chaney Briar	58	0.03	242	0.07
Myrica cerifera	Wax Myrtle	27	0.02	234	0.07
Myrsine floridana	Colic Wood	36	0.02	197	0.06
Pinus caribaea var. bahamensis	Bahamian pine	149	0.08	190	0.06
Diospyros crassinervis	Featherbed	72	0.04	163	0.05
Ernodea littoralis	Golden Creeper	20	0.01	125	0.04
Adiantum capillus-veneris	Maiden Hair	243	0.14	96	0.03
Psychotria ligustrifolia	Smooth Wild Coffee	93	0.05	80	0.02
Randia aculeata	Box Briar	38	0.02	76	0.02
Tabebuia bahamensis	Five finger	119	0.07	66	0.02
Morinda royoc	Wild Mulberry	11	0.01	60	0.02
Chrysobalanus icaco	Coco plum	0	0.00	44	0.01
Euphorbia prostrata	Lay Flat Spurge	64	0.04	36	0.01
Fern (unidentified)		0	0.00	36	0.01
Agave bahamana	Bahama Century Plant	1	0.00	33	0.01
Rhynchospora floridensis	White Top, White-headed Rush	0	0.00	33	0.01
Caesalpinia bahamensis	Bahama Brasiletto	109	0.06	31	0.01
Heliotropium angiospermum	Rooster Comb	15	0.01	30	0.01
Turnera ulmifolia	Bahamian Buttercup	0	0.00	24	0.01
Stenaria nigricans	Star violet	0	0.00	21	0.01
Trema lamarckiana	Pain-in-Back	0	0.00	15	0.00
Sideroxylon salicifolium	Willow Bustic	0	0.00	12	0.00
Unknown		0	0.00	12	0.00
Piscidia piscipula	Jamaican Dogwood	0	0.00	7	0.00

Pteridium aquilinum	Bracken Fern	0	0.00	7	0.00
Bourreria succulenta	Strong Back	13	0.01	1	0.00
Pecluma plumula	Comb Fern	0	0.00	1	0.00
Petitia domingensis	Bastard Stopper	0	0.00	1	0.00
Leucaena leucocephala	Jumbey	55	0.03	0	0.00
Zamia pumila	Coontie, Bay Rush	53	0.03	0	0.00
Coccoloba diversifolia	Pigeon Plum	48	0.03	0	0.00
Tetrazygia bicolor	Wild Guava	29	0.02	0	0.00
Lantana x bahamensis	Wild Sage	11	0.01	0	0.00
Chiococca alba	Snow Berry	4	0.00	0	0.00
Total number of individuals (N =)		1784	1	3336	1.00
Shannon's Diversity Index		3.00		1.18	
Number of species per wellfield		26		31	
Total number of species		37			

Assessment of both wellfields revealed that W6 had complete tree mortality, whereas only 16% of trees were dead in W1 (Table 4). The total basal area per acre in W1 was greater than in W6 (Table 4), which can be attributed to the number of live pines in W1; however, the density of dead stems was greater in W6. This corresponds with the greater amount of flooding observed in W6 compared with W1 during Hurricane Dorian, in addition to the higher salinity and conductivity values observed during the assessment period post-hurricane.

Additionally, the pine trees in W6 had a decay class between 2 and 3 versus W1 with pine trees in a decay class between 1 and 2, which indicates that the trees in W6 are decaying at a more rapid rate than trees in W1. As trees draw up water from the groundwater table for transpiration, the absence of large trees in W6 may contribute to an increased recharge of the freshwater lens over time. However, decomposing trees may also affect water quality.

Table 4

Condition of Pine Trees Assessed in Wellfield 1 and Wellfield 6

Wellfield	Condition	Number of trees	Total basal area per tree (m^2)	Total tree volume (m^3) per square meter
1	Alive	42	1.12	11.6
	Dead	8	0.17	2.09
	Sum	*50*	*1.29*	*13.68*
Total Basal Area per Acre			52.34	
6	Dead	35	0.48	4.93
Total Basal Area per Acre			19.34	

Management Strategies and Research Opportunities

Groundwater Restoration

Due to the extensive flooding at W6, this wellfield is anticipated to take longer to recover than W1, which is already showing signs of improvement. Although W6 salinity and TDS concentrations have decreased two years post-Hurricane Dorian from initial values, the concentrations remain very elevated and exceed drinking water standards.

Evaluation of Managed Aquifer Recharge

Managed Aquifer Recharge (MAR) could be a potential method for diluting salt concentrations in groundwater and for establishing hydraulic conditions that preserve and enhance freshwater lenses in the subsurface. Rainwater was identified as the most promising potential source for MAR. Based on data collected in Freeport by the Bahamas Department of Meteorology between 2012 and 2020, a mean annual rainfall of 1600 mm was calculated by Klausner (2022). Surface water is very limited on the island, as low terrain and natural permeability of the limestone does not allow the formation of larger surface water bodies (ICF Consulting, 2001). Furthermore, wastewater is not collected in a centralized wastewater treatment system to consider it as a water source in sufficient quantity nor quality.

Many of the available aquifers on the island could potentially be suitable for water storage due to their high hydraulic conductivity and storativity. Nevertheless, restrictions exist for the location of potential MAR schemes, such as flood-proof design in W6 because of low terrain levels. Saltwater intrusion into W6 could be mitigated by recharging the freshwater lens with injection wells installed at locations that are safe from floods. Freshwater sources could be rainwater or desalinated water obtained from reverse osmosis plants. Neither the necessary quantity of fresh water nor the timeframe to dilute the brackish water in the aquifers of W6 has been estimated, to date. Numerical modelling studies could be conducted for estimating water quantities and thus predicting the feasibility of such approaches. Additional geophysical, groundwater level and salinity level measurements should be carried out to reach prediction integrity with the models.

Because of the flooding potential, this study investigated potential suitable locations for MAR on areas of the island with higher laying terrain. The Intergovernmental Panel on Climate Change (2007) reported that Grand Bahama is particularly threatened by climate change effects with sea level rise due to its low terrain levels (60% of the island have elevations lower than 1 m.a.s.l.). The areas around W1, W3, and W4 were identified as potentially suitable. In a study by Little et al. (1977) high evapotranspiration rates of 75% were identified on the island. Due to the high evapotranspiration losses, suitable MAR types should enable comparatively rapid groundwater recharge. Since rainwater would be the main water source for MAR, an urban MAR method is recommended, potentially also including collected runoff water from roofs and streets, if sufficient water quality can be assured (Page et al., 2018). To identify the full potential of urban MAR methods on Grand Bahama, further hydrogeological and geophysical investigations are recommended to identify the flow regime in the elevated terrain of Grand Bahama. This would allow the identification of suitable locations for recharge schemes.

Groundwater Adaptation Strategies

Strategies should be developed for sustaining future independent and sustainable water supply on the island of Grand Bahama. The Bahamas is particularly vulnerable to the effects of climate change, such as extreme weather events with tropical storms and sea level rise (Intergovernmental Panel on Climate Change, 2007). Water management is a key element in social and economic development on the island (Cashman et al., 2010). A potential option to counteract negative effects of climate change on water resources on Grand Bahama could be the diversification of water sources to reduce demand on the freshwater lens. A combination of drinking water sources from groundwater and desalinated water, using reverse osmosis, is already available to date. However, the economic cost and environmental impacts due to high energy demand and greenhouse gas emissions warrant additional sources to be investigated. A wastewater treatment system could be installed on the island, and treated wastewater could be a potential source of water supply. Radcliff and Page (2020) report that climate change effects, such as droughts, have been a driving factor to implement wastewater treatment and desalination plants in Australia.

Reducing demand of the freshwater lens is an important adaptation strategy. Water policies for water reduction, such as restricting the use of private pools or garden watering could be established to ensure conservation of freshwater resources. Water leakages from the water supply system in Grand Bahama are estimated to account for 30-40% of water losses. Currently, leak detection and rehabilitation programs are in place. GBUC has installed meters to monitor water usage, and additional renovations of the water supply system could decrease water demand significantly and promote a sustainable drinking water supply on the island.

Increasing storage in the freshwater lens is also a critical adaptation measure to address climate change. MAR could be a cost-efficient potential solution to supply water to the island and store water for future demand in comparison to water treatment (Damigos et al., 2016). Diamond and Melesse (2016) evaluated the potential for MAR with runoff harvesting from roads on the neighbouring island, New Providence. As on Grand Bahama, a drainage well system already exists for the prevention of road flooding, which could be used as input for MAR. However, due to the lack of water treatment, road runoff could pollute the aquifer with contaminants (e.g., tire wear, oil, heavy metals, and suspended solids). The existing wells could be expanded by drilling additional wells and adding filters for water purification. Extending the existing drainage well system on Grand Bahama as well as making improvements to water quality treatment could be an additional source of water supply for the island.

Alternative Potable Water Sources

The feasibility of long-term restoration of the aquifer is challenged by the costs associated with these endeavors. MAR schemes have the potential to be cost prohibitive, and installation of a reverse osmosis plant would add significantly to the annual costs of the GBUC. Reverse osmosis plants are used on many other islands throughout The Bahamas but are currently not in use by GBUC, with the exception of the small portable unit used to address salination of the wellfields. Although reverse osmosis is often considered as an alternative source of potable water on islands when groundwater supplies are not accessible, it has many drawbacks when considering its use on Grand Bahama. In addition to restoring the freshwater lens, other methods exist for increasing water supply on the island.

Desalination

Following the inundation of the wellfields, GBUC began operating a portable desalination system on saline water pumped from W1 to ensure potability of the water being pumped to residences. To sustain long-term desalination efforts at a rate that is sufficient to meet demand, GBUC is currently partnering with outside organizations to build a reverse osmosis plant to provide potable water for the island. Desalination provides valuable drinking water sources for small islands and other areas that are threatened by a lack of fresh water. However, reverse osmosis plants are very energy intensive and contribute to greenhouse gas emissions (Schunke et al. 2020). As small islands are facing the effects of climate change, such as Grand Bahama with Hurricane Dorian, reliance on reverse osmosis plants can negatively impact long-term sustainability. Alternative methods are also important to consider to reduce reliance on fossil fuels, to minimize contribution to greenhouse gas emissions, and to diversify sources to avoid over-reliance on any one method.

Ocean Thermal Energy Conversion

In The Bahamas, sustainable development is challenged by energy production and water supply, as is typical of small island nations. Ocean thermal energy conversion (OTEC) is a technique that can produce both energy and fresh water, enhancing the potential for the country to become more resilient against climate change (Fujita et al., 2012). OTEC has been considered an energy and potable water source since first investigated in Hawaii in 1974 (Gill & Rocheleau, 2009). The Bahamas exhibits inverted geothermal conditions in subsurface waters, which is ideal for the development of OTEC. In larger continental countries, geothermal conditions typically get warmer with depth, whereas in The Bahamas the high exchange with ocean water results in inverted conditions where water gets cooler with depth.

In the deep subsurface of The Bahamas, the temperature and salinity of the groundwater indicate a high exchange between subsurface and ocean waters. Additionally, the high transmissivity and hydraulic conductivity of Lucayan limestone promote the abstraction of groundwater and return of water flows. OTEC could provide an opportunity to extract deeper saline waters for conversion to fresh drinking water, reducing demand on the fragile freshwater lens, while also providing energy and reducing overall fossil fuel reliance.

Rainwater harvesting

Rainwater harvesting is a sustainable method to further promote water security on Grand Bahama. Rainwater collection involves storing precipitation through catchments and proper storage of water, instead of allowing it to run off (Helmreich & Horn, 2009). The Bahamas has a subtropical climate that is conducive to rainwater harvesting as precipitation is distributed throughout the year. Indeed, the historical method of water supply in The Bahamas was rainwater harvesting from individual roofs and storage in tanks. This method still plays a role on smaller islands, especially in the southern Bahamas (Whitaker & Smart, 1997), but overall only around 3% of water supply is sourced from rainwater harvesting in the Bahamas (USACE, 2004)

Rainwater harvesting is a common practice throughout the Caribbean. For example, Barbados, Grenada, Antigua and Barbuda implement this practice (Ekwue, 2010), and installations of rain catchment systems of a certain size are required when building a new house in Turks and Caicos (Whitaker & Smart, 1997). Investment and research opportunities exist in the field of rainwater harvesting, especially for small island developing states, where it is a more suitable method. Harvesting decreases the demand on groundwater resources while providing avenues to educate citizens in water conservation. As stronger storms are becoming more prevalent, diversifying water resources is imperative to ensure water is available in dire circumstances. Grand Bahama has the land capacity to facilitate large rainwater storage facilities, and through encouraging harvesting by residents, implementation can be successful.

Soils

The silt crust will form an even layer and partially breakdown through natural weathering into the ground beneath, adding nutrients to the soil. The electrical conductivity of the soils should be monitored periodically to better understand recovery times on Grand Bahama Island. Keim et al. (2019) measured salinity in soils and sediments affected by storm surge flooding by Hurricane Katrina in Louisiana, United States, and found elevated values 11 years after the event and estimated recovery rates to pre-hurricane salinity to be at least two decades. As electrical conductivity measurements on Grand Bahama Island are moderate in 2022 the recovery time should be shorter than in Louisiana, although it will be affected by any future flooding events.

Forests

The absence of mature pine trees in W6 was not unexpected, as Hurricane Dorian settled over the eastern part of Grand Bahama for several hours. The substantial storm surges inundated the region resulting in hypersaline conditions. *Pinus caribaea* var. *bahamensis* does not germinate under saline conditions and requires a slightly acidic soil pH to grow (Hamilton et al., 1993). However, the volume of wood available had the potential to be harvested soon after the storm for use as treated lumber or wood pulp. One major limitation is that the cost to remove the timber would have outweighed the value of timber sales.

W1 had greater plant diversity and is located in an area that was not as heavily impacted by Hurricane Dorian. The healthy appearance and presence of actively growing pine trees suggest that the undamaged landscape in W1 has the potential to undergo natural regeneration at a fast rate and maintain a range of species in relatively even numbers. However, W6 had greater numbers of rapid-growing, resilient species like poisonwood and silver thatch palm, which were the most dominant species. The presence of pine seedlings in W6 also indicates that natural pine regeneration is occurring, which suggests that the salinity in the soil water is low enough to allow for seed germination and plant development. Overall, the landscape in W6 had a dry, damaged appearance with several woody shrubs and low, fast-growing, herbaceous species.

The current species' composition in both wellfield sites suggests that the pine forests are showing signs of recovery and are, therefore, quite resilient. Since these data were collected more than two years after the catastrophic storm, it can be deduced that once unfavourable environmental conditions are reduced, the forested areas will be able to regenerate and recover. The more forested areas showed greater signs of regeneration, while the more open areas with no pine trees showed slower rates of recovery. Land cover is critical for protecting the soil conditions and freshwater lens, and shifting species composition and the presence of dead trees has the potential to impact the amount of water being used by plants and the amount of water recharging the freshwater lens. Therefore, restoring the forest cover is an essential component to address the restoration of the freshwater lens post-Hurricane Dorian.

Management Amidst Climate Change

Weather and climate are arguably the main drivers of freshwater resources. To develop a resilient water supply system, water resource managers must anticipate and account for changes in climatic variability and extremes. The scientific community and agencies such as U.S. National Oceanic and Atmospheric Administration and National Aeronautics and Space Administration have developed tools and services to help communities increase their capacity building on resilience to climate change. As an example, the North American multi-model ensemble (Becker et al., 2022) provides 12-month forecasts of precipitation and other atmospheric variables on a global scale. Such information, if properly utilized, can inform water managers and help them optimize some of the strategies mentioned previously (e.g., rainwater harvesting). Furthermore, analysis of current state-of-art climate projections from CMIP6 (Eyring et al., 2016), in combination with sea level rise scenarios for climate impact assessment on the island's water resources, is necessary to develop effective mitigation strategies. Coupling information from seasonal forecasts and climate projections with numerical groundwater models can offer a very important prediction framework that can be used for both monitoring groundwater resources and scenario analysis for future climate conditions in western Grand Bahama.

Conclusions

To date, the water quality of the freshwater lens in the W1 and W6 wellfields has not been restored to pre-Hurricane Dorian levels, and the impacts on soils and forested ecosystems in western Grand Bahama are still evident. Despite elevated salinity in the wellfields for more than two years post-Hurricane Dorian, W1 levels are starting to decline and are anticipated to recover faster than W6, where the flooding was deeper and the current salinity levels are higher. Natural recovery of the freshwater lens and forests is anticipated to take decades, and, therefore, further studies and remediation efforts are essential for recovering the natural resources of western Grand Bahama.

This collaborative effort provides a comprehensive summary of research efforts in the study area in the two and a half years following Hurricane Dorian. Further studies quantifying fresh water and characterizing water quality, soil, and land cover in the wellfields are critical to evaluate how Grand Bahama continues to recover from this catastrophic event in the long term. Small islands are increasingly threatened by extreme events, such as hurricanes and sea level rise associated with climate change, and these results from Grand Bahama are important for indicating how other Bahamian islands and small islands globally may recover from similar events.

Acknowledgments

The authors would like to thank Carlton Watson and Christopher Russell for their contributions to the project, Jerube Hepburn and Gilbert Russell for assistance with field visits, and Andrew Curry and Cliff Bethel who assisted with forestry data collection. The authors are also grateful for comments by an anonymous reviewer on an earlier version of this manuscript.

This paper and portions of this work are a product of the project "Strengthening of Forests Through Groundwater Restoration" sponsored under the Bahamas Protected Areas Fund and the Caribbean Biodiversity Fund and financed by the German Federal Ministry for Economic Cooperation and Development through KfW. Part of this research is based upon work supported by the National Science Foundation under Grant No. 2015311. The WASH programme carried out by IsraAID was funded by The United Methodist Church, and additional assessments were the joint efforts of IsraAID, Israel Water Authority, and the Israeli Ministry of Foreign Affairs. Initial site assessments immediately post-Hurricane Dorian were funded by the Water and Sewerage Corporation, as well as the United Nations Educational, Scientific, and Cultural Organization–Intergovernmental Hydrologic Programme. A portion of this research was conducted under Research Permit #166505 from the Department of Environmental Planning and Protection in The Bahamas.

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